Report on CCD Filters

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Introduction.

COPS (CCD Optical Alignment Sensor) uses linear CCD arrays as sensing elements. A laser beam is modified, by a cylindrical lens, into projecting a line of known position in space. Two cylindrical lenses, with either one or two laser modules, can thus produce a cross-hair pattern. The CCDs (four in number) are arranged in such way that each one of them detects one of arms of the laser cross. The centroids of the laser light detected by the CCDs are then correlated with the positions of the projected laser lines in space.

The sensitivity of the CCDs is such that room light can also be detected, producing an unwanted background under the laser profile. That background reduces the dynamic range of the CCD sensitivity, because the latter has a saturation point; when the background reaches that saturation point, the laser light would not be detected. But even before that happens, the laser intensity must be reduced in such a way that the laser peak is not saturated, which would complicate the finding of the centroid. Thus, the need for a filter.

The filter.

What has become know as 'the filter', is a combination of absorber, and filter. A filter will eliminate the background caused by the room illumination. However, because the intensity of the laser beam decreases with the distance from its source, CCD sensors at different locations must have different sensitivities to the laser light; therefore, the filter must also reduce the sensitivity of the sensor, namely it should act as an absorber. There are other ways to reduce the sensitivity of the sensors, and they will be discussed later on.

The original COPSs were uni-directional, namely, they could only detect the laser beam illuminating them face-on. Even in this simpler case, tuning the absorption of the filters is not trivial; the laser beam intensity varies by three orders of magnitude (in the 14m SLM alignment line).

In the COPS II, the same CCDs used in COPS are now turned 90 degrees, in order to detect the laser beams coming from either direction. This is accomplished by attaching a "collector-wedge" onto the CCD window. The collector-wedge, or simply wedge, is a prism made of a transparent material (Lucite, poly-carbonate, glass), and glued to the CCD face; its primary function is to provide surfaces on which the laser lines can be projected, and therefore detected, no matter the direction they come from, by the CCD pixels. That makes the COPS II into a bi-directional sensor. But it also comes with a price: the added complexity of the sensor.

The requirements on a filter for a bi-directional sensor (see Fig. 1), including those that must be satisfied by the uni-directional filter, are:

1) it must reduce the effect of the ambient illumination,

2) It must have variable absorption coefficients, covering a range of three orders of magnitude,

3) It must not degrade the natural beam width as detected by the sensors, at the farthest sensor position, by more than about 50%.

4) It must be uniform and optically stable.

5) It must project the laser line image to the CCD pixels,

6) It must block the detected laser line, so it does not interfere with downstream sensors.

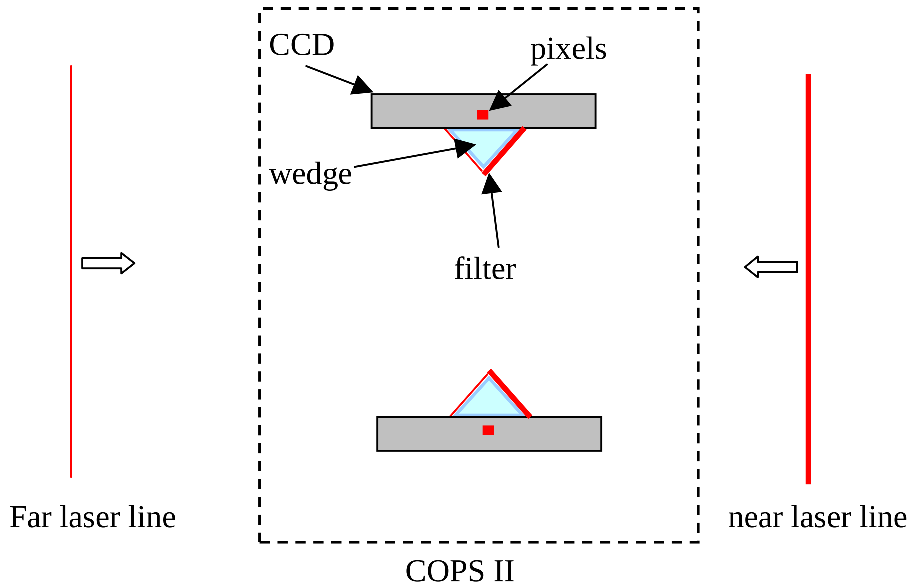

Fig. 1. Bi-directional sensor filter

Discussion on Requirements.

Requirement 1) is basically to produce a low background signal. We can specify that the background level be lower than 1000 ADC counts (our maximum being 4000), under normal laboratory conditions.

Requirement 2) is imposed by the attenuation of the beam intensity with distance. Sensors near the laser source must have a much heavier absorber, than those far away.

Requirement 3) relates to the width of the beam profile, as seen by the CCD pixels.

Requirement 4) ensures that measurements performed with the sensor are accurate and reproducible.

Requirement 5) is part of the basic bi-directional technique. The laser beam projects a line on the CCD wedge that is then detected by the CCD pixels.

Requirement 6) is also part of the bi-directional technique. The laser beam intercepted by the wedge should not be allowed to continued past it, otherwise it may interfere with the other sensors. In other words, the wedge can not be transparent.

Other desires (wish-list), as well as other not considered capabilities of the CCD technologies (exposure control, for instance), will of course modify the above list of requirements. However, I believe that the six requirements specified above are necessary, and also sufficient, to have a working bi-directional sensor.

Some of our colleagues in the EMU alignment group, and outside it, believe that another basic, if not the most important, requirement, is for the filter to provide a narrow and gaussian-like beam profile, otherwise the centroid finding can not be successful. They are mistaken. There is nothing to gain, and what it is worse, the insistence in using gaussian fitting is the cause of most of the problems in processing the data through the “first level analysis”. In addition, filters are not the main reason beam profiles are non-gaussian. The largest contribution to the beam width comes from the natural beam divergence: several meters downstream from the laser source, the beam divergence becomes noticeable, and at larger distances the beam profile can no longer be adequately fitted with a gaussian curve. Our colleagues working on the Link alignment (with ALMY sensors), who use more sophisticated laser sources, face exactly the same problem, at shorter distance than ours. How do they deal with it? They abandon fitting and resort to simple centroid finding procedure. By the way, they insist in taking data with lights off, even though they could have fancier optical coating, for filtering, on their sensors. The bi-directional technology also affects the width of the beam profile, as explained before. That is a trade-off for the convenience of new technique.

At Northeastern, we have done all the tests and calibration work on the COPS, and COPS II, using a simpler peak finder algorithm that does not depend on the beam profile having a well behaved gausian-like shape. We have demonstrated position resolutions, linearity, and measurement stability of few microns, well beyond the requirements of the EMU alignment.

Another possibly important consideration is that the peak finder algorithm may eventually be ported to the on-board DSP. It is hard to imagine that a gaussian fitting procedure, with floating background to boot, can be implemented in such a limited platform. In that case all the experiences obtained with the current peak finder would be for nought.

Other approaches to handle differences in laser intensity.

Besides using varying thickness of paint, or other covering material, on the CCD wedge itself, one can change the laser intensity according to the sensor one is about to expose and read; or one can change, electronically, the CCD exposure time.

The laser intensity can be modulated by a) voltage control of its output, and b) the use of variable neutral density filter. Both of these techniques add some complexity, as well as time, to the DAQ process. Modulating the laser output requires, in addition to the extra electronics, additional steps in the DAQ process, which must now include changing the laser intensity and waiting for it to stabilize.

The CCD exposure time is determined by the interval between two readout gate pulses (these control the transfer of charge from the photo-sensors to the CCD shift registers). That interval can not be smaller than the total shift time for all the pixels, otherwise some of the shift registers might not be empty. It seem worthwhile to explore the possibility of controlling the exposure time.

Northeastern's program.

We have assumed from the very beginning that the electrical vinyl tape was a good temporary solution. It has worked for us, and extremely well at that. Vinyl tape satisfies all the requirements, listed above, for a good filter, with the possible exception of the requirement for optical stability (it tends to contract and even peel off, if not properly applied or supported). On the other hand, vinyl tape is extremely easy to apply; simple to tune to the right absorption over a very large range of beam intensity variations; it can be replaced or modified to cope with unexpected changes in room illumination. It is in fact an ideal filter/absorber for sensor development.

It is possible to design ways to make vinyl tape into a more permanent filter (by providing external support, for instance), but there are other simpler and more reliable ways to achieve similar and better effects.

We intent to pursue a substantial reduction, if not elimination, of the background in the CCD spectrum, by both filtering and shading. The latter refers to the use of thin plate elements to screen ambient light.

The issue of absorption will be also pursued along two independent approaches: the use of stable paint coating, and the control of exposure time in the CCD.